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INVESTIGATIONS OF NEAR WAKE FLOW FIELD AND HEAT TRANSFER ON TWO DIMENSIONAL AND AXIALLY SYMMETRIC BODIES AT SUPERSONIC SPEEDS

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Technion - Israel Institute of Technology
Haifa, Israel

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TECHNION – ISRAEL INSTITUTE OF TECHNOLOGY
DEPARTMENT OF AERONAUTICAL ENGINEERING
HAIFA, ISRAEL

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Abstract

This report summarizes some of the research carried out under contract F 61052-69-C-0020 during the year 1st September 1968 to 31st August 1969.

Laminar and transitional heat transfer rates were measured in various base type separated flows in the shock tube. It was found that maximum and average heat transfer rates are correlated by the parameter $(h Re_L^{1/2}/L)$ for models with an initial boundary layer and by Re_L for models with leading edge separation.

The application of the hot wire technique for measurements of the flow field in the supersonic near wake is studied. It is shown that using the measurements of a hot wire probe and a total pressure probe enable the determination of all the required physical parameters of the dissipative flow field in the near wake. The flow field behind a blunt two dimensional base model is measured at Mach number of 2.25 and $Re_L = 1.5 \times 10^6$. Mach number and total temperature profiles are determined and the various zones in the flow field are identified.

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LIST OF SYMBOLS

h	step height
Kn	Knudsen number
L	length of model ahead of separation, Hot-Wire length
M	Mach number
M_f	free stream flow Mach number over the model
M_s	shock Mach number
Nu	Nusselt number
Nu_x	local Nusselt number
Nu_m	measured Nusselt number
P_1	initial pressure in the shock tube low pressure section
Pr	Prandtl number
q	local heat transfer rate
$q_{f.p.}$	attached flow heat transfer rate
Rw	wire resistance
Re	Reynolds number
Re_h	Reynolds number based on h
Re_x	local Reynolds number
Re_L	Reynolds number at the separation position
T	temperature
t	time
V	voltage
x	local distance
Δx	distance from separation position
[illegible]	resistivity
δ_L	boundary layer thickness at separation
η	recovery temperature ration, Tad/To

LIST OF FIGURES

I. INTRODUCTION

The present report summarizes some of the research work carried out under contract F 61052 69 C 0020 during the year 1st September 1968 to 31st August 1969. This year's program included an extension of the heat transfer studies of base type flows in the shock tube which are discussed in Part II, as well as a program of near wake flow field study using the hot-wire anemometer discussed in Part III.

II. Heat transfer rate measurements in base type flows on the shock tube

Flow separation at supersonic and hypersonic speeds is known to have strong effects on the heat transfer rates to body surfaces particularly in the reattachment regions. In general, it was found that heat transfer rates are decreased in the "dead water" zone and increased in the reattachment zone in relation to flat plate heat transfer rates under similar flow conditions. The net effect of this variation of heat transfer on the heat transfer rate in the separated flow region as a whole is not easily determined since in many cases the increase in the heat transfer rate in the reattachment zone is much greater than the corresponding reduction found in the "dead water" zone. For the past several years, heat transfer rates in separated flows have been studied at the Aerodynamics Laboratory of the Technion's Aeronautical Department supported in part by EOAR contracts. These studies were conducted in the 3" x 3" shock tube and have included the following model configurations :

(1) Two-Dimensional Backward Facing Step (Ref. 1).

(2) Axisymmetric Backward Facing Step (Ref. 2).

(3) Two-Dimensional Blunt Base (Ref. 3).

(4) Sharp Protruding Leading Edge (Ref. 4).

(5) Two-Dimensional Leading Edge Separation Bubble (Ref. 5).

In this report a summary of some of the more significant results of the previous studies is presented and is also correlated to determine the main parameters affecting the data.

The shock tube has been found to be a very useful facility for heat transfer studies. Using thin (or thick) film platinum resistance thermometers local heat transfer rates can be measured to an accuracy of better than $\pm 15\%$ and even up to $\pm 5\%$. These are as good as, and in many cases, even better accuracies than can be obtained in heat transfer measurements in conventional wind tunnels. The feasibility of measurements of heat transfer in separated flows in the shock tube and the shock tunnel was discussed by a number of investigators (Ref. 6, 7, and 8). Thus, based on measurements in the shock tube our previous results indicated that laminar heat transfer rates ~~is~~ in separated flows (with an attached boundary layer ahead of separation) can be correlated using the parameter $hRe_L^{1/2}/L$. This parameter is proportional to the ratio of step height to boundary layer thickness at separation, δ_L, and was found to correlate the laminar separated region pressure field as well. It is interesting to note that some measurements of the heat transfer rate distribution on various backward facing step models in a continuous supersonic wind tunnel reported in Ref. 9 support this correlation. Comparison of the shock tube data and the wind tunnel measurements reported in Ref. 9 are included in this paper. Although the flow conditions in the two experiments are very different, particularly the large differences in stagnation to wall temperature and the state of the boundary layer of

these experiments, the heat transfer rates in both experiments are found to be related by the parameter $hRe_L^{1/2}/L$.

The experimental apparatus and results are discussed in detail in Ref. 10. The main results are discussed herein. The variation of the local heat transfer rate along the model length as shown in Figs. 3, 4, 5 and 6 for various Mach numbers indicates that, for a given model, there is only slight variations in the position of the beginning of the reattachment zone and the point of the maximum local heat transfer rate as shock Mach varies from 5 to 10. Detection of any movement of these positions, however, was limited by gage size and location. Of importance is that all the curves exhibit qualitatively similar variations of local heat transfer rates. This similarity of the heat transfer rate distributions is found in spite of large variations (flow Mach numbers and stagnation to wall enthalpy ratios) as well as model geometry. With the exception of the leading edge separation bubble on the blunt nosed body, the heat transfer distribution over the sharp leading edge model, the backward facing step and the axisymmetric step models definitely show a zone of low heat transfer rate in the "dead water" zone. Following this is the reattachment zone as signified by a sharp rise in the heat transfer rate. It is expected that following reattachment the heat transfer rates would approach the flat plate values. In fact, many of the curves exhibit this tendency, however, in some cases, the gages available on the model were not sufficient to show this trend.

The extent of the low heat transfer rate zone in the "dead water" zone is found to be about 1 to 1.5 step heights from the two-dimensional and axisymmetric backward facing steps (Figs. 3 and 4) while it extends to about 4 step heights for the sharp leading edge model (Fig. 5). The maximum

transfer rate in the reattachment zone is found to occur at about 4 to 6 step heights for the two-dimensional and axisymmetric backward facing steps (Figures 3 and 4) and at about 8 step heights for the sharp leading edge model (Fig. 5). For the leading edge bubble case, closure of the bubble and reattachment is indicated at about 3 nose heights behind the leading edge (Fig. 6).

The results of wind tunnel measurements of the heat transfer rate distribution behind a backward facing step reported in Ref. 9 are also included. It is seen that the wind tunnel data seems to be extended so that the peak values of heat transfer rates are obtained after about 12 to 15 step heights while the shock tube data indicates that this occurs after about 4 to 6 step heights. On the other hand the results of Ref. 11, which are also obtained in the wind tunnel, show peak values at about 2 to 3 step heights. This does raise the question of whether or not these differences are dependent on errors due to the various experimental methods used. The heat transfer measurements in the wind tunnel require measurements of a number of physical parameters which must be corrected and are sensitive to errors, while the measurement of heat transfer in the shock tube involves a direct measurement of a single precalibrated transducer . Most separated flow measurements do indicate reattachment at 2 to 4 step heights therefore provide an additional support for the shock tube measurements.

The maximum heat transfer rate at reattachment is correlated by the use of the non-dimensional parameters as follows :

(1) in cases of an initial boundary layer at separation

$$q = A(h\mathrm{Re}_L^{1/2}/L)^n \quad q_{f.p.}$$

(2) in cases of zero initial boundary layer at separation

(e.g. - sharp leading edge);

$$q = BRe_h^m \cdot q_{f.p.}$$

The empirical values of the parameters A and n and B and m for the various geometries are presented in Tables 1 and 2, respectively and in Fig. 7. The maximum heat transfer rate values obtained in the wind tunnel study of Ref. 9 are found to be in surprisingly good qualitative agreement with the shock tube data in spite of previous remarks and of the extreme differences in stagnation to wall enthalpy as well as state of flow. This seems to suggest that the heat transfer in laminar separated flow is not too sensitive to variations in flow Mach number (at least in the range of Mach number 1.5 to 3.0) and stagnation to wall enthalpy. The dominating parameter is found to be the value of $hRe_L^{1/2}/L$ for cases with initial laminar boundary layer thickness or Re_h for cases of zero boundary layer at separation. An additional important parameter seems to be the state of the boundary and mixing layers and the relative position of transition. It is suggested in our measurements and in those of Baker and Martin (Ref. 11) and actually demonstrated in the measurements of Sanford and Ginoux (Ref. 9) that when transition appears ahead of reattachment very high values of heat transfer rates at reattachment are experienced. In the completely laminar separation case the heat transfer rates are relatively low and even at reattachment the maximum values are not much larger than the corresponding attached flat plate values. In the completely turbulent case maximum values are in order of 2 to 4 times the attached flat plate value as found by Naysmith (Ref. 12) and Thomann (Ref. 13). However, in the transitional flow

cases, which we assume occured in the shock tube tests at the higher Reynolds numbers, extremely high peak heat transfer rates of the order of 5 to 7 times the laminar flat plate values were detected. The measurements in Ref. 9 tend to support the explanation that these high heat transfer rates are associated with the movement of the transition point ahead of the reattachment position into the mixing layer. Therefore the present correlation may be taken to cover both the cases of completely laminar separation and transitional cases where the boundary layer is laminar ahead of separation and transition occurs at a position between separation and reattachment.

III. Application of hot wire anemometer for supersonic near wake studies

Determination of the physical parameters in the near wake flow require the measurements of at least three independent local physical quantities. In most previous wake flow measurements one physical parameter, e.g. - the total temperature has been assumed to be constant in the flow field. Measurements using the hot wire probe and a total pressure probe enable the determination of all the required physical parameters of the dissipative flow field in the near wake. Due to its relatively small dimensions, fast response and high signal to noise output the hot wire anemometer is particularly suitable for flow measurements in the wake. This part summarizes the method of measurements and data analysis for such measurements in the turbulent near wake behind a two-dimensional blunt base.

The measurements are conducted in the 10 cm x 10 cm supersonic wind-tunnel at Mach number 2.25 and Reynolds number based on model chord of 1.5×10^6. The model is a wedge-flat plate with a blunt base and spans the wind-tunnel test section. The hot wire probe is a 0.005 mm platinum coated tungsten wire soldered to the two support needles. The wire length is about 1 mm (wire aspect ratio of about 200). Two probe geometries (Fig. 8) were tested in order to check the effects of these supports on the directional wire response in the recirculating flow. Both probe supports gave essentially identical response, so that this effect is found to be very small. The block diagram of the measuring system is shown in Fig. 9. Each probe is calibrated to determine its resistivity coefficient and is pretested in a calibration wind-tunnel. A detailed description of the experimental system is presented in Ref. 14.

The anemometer response is due to heat transfer from or to the probe's

wire from the flowing fluid. The analysis of the data requires finding a relation between the heat exchange coefficient, indicated by the wire Nusselt number, and the local Mach and Reynolds numbers of the flow. Empirical correlation of available data was presented in Ref. 15. For a constant temperature anemometer, used in the present investigation, the probe response is

$$Nu_m = \frac{\kappa_r}{\pi L} \frac{R_r}{R_o} \left. \frac{d(V^2/R_w)}{d(R_w - Raw_m)} \right|_{i>0} \qquad (1)$$

and the relation for Nu(Re,M) is defined in Ref. 15 by relations of the form

$$Nu(Re,M) = Nu(Re,\infty)\ \varphi\ (Re,M) \qquad (2)$$

and is shown in Fig. 10. In a dissipative flow it is convenient to use a modified correlation of equation (2) writing the Mach number as a function of Nusselt and Reynolds numbers shown in Fig. 11.

The adiabatic temperature measurement is then corrected for the Knudsen and Mach numbers effects by the relation (Ref. 15)

$$\eta = \eta\ (M,Kn) \qquad (3)$$

shown in Fig. 12.

Thus, the first stage in the data analysis is calculating for each measured hot wire output the local Nu_m and Taw_m, using the proper relations represented by equations (1),(2) and (3). These profiles are nomalized by the free stream values in order to account for probes errors and losses. This calculation is performed on the Elliot 503 computer using the program shown in block diagram in Fig. 13.

The local Mach and Reynolds number profiles are evaluated from the previously determined Nu_m and Taw_m by an iteration procedure shown in a block diagram in Fig 14. For this calculation the local total pressure is obtained from previously measured pitot pressure profiles presented in Ref. 16.

The hot wire output at various wire overheat values is shown in Fig. 15. From these results the profiles of the Nusselt number and adiabatic temperatures are evaluated. Profiles of local Mach number and total temperature are then calculated using the pitot pressure data and the iteration procedure shown in Fig. 14. Typical profiles of Nu_m and Taw_m and of Mach number and T_t measured at about one base height behind the model are shown in Figures 16 and 17 respectively. A map of the Mach number and of the total temperature in the near wake is shown in Figures 18 and 19 respectively. A shadow photograph of the corresponding flow field is shown in Fig. 20. Using these measurements the various flow regions can be now specified as shown in Fig. 21.

It is found that there is an excellent correspondence between the hot wire measurements and flow field photographs in respect to the positions of the lip shock, trailing shock, expansion fan region, etc.

Furthermore, these measurements do show that the clearly seen bright white line emanating from the base corner does correspond to the position of peaks in the total temperature profiles. These peaks are found to be near the outer edge of the mixing zone. This may indicate a layer of high shear in this part of the mixing zone.

In the "dead water" zone the hot wire probe is sensitive to the absolute value of the local velocity with no regard to its direction. It is therefore interesting to note that Mach number values of about 0.4 to 0.6 are measured near the base. The Mach number variation on the wake center line is shown in Fig. 22. Near the reattachment zone the present iteration procedure failed to converge so that no Mach number values are available there. This effect may be due to either very high shear values at this zone (which cause erroneous probe output) or due to large flow inclination which results in considerable error in the total pressure measurements.

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TABLE 1.

AVERAGE AND MAXIMUM HEAT TRANSFER RATE PARAMETERS FOR CASES WITH INITIAL BOUNDARY LAYER.

$$q = A(hRe_L^{1/2}/L)^n \quad q_{f.p.}$$

	$q_{ave}/q_{f.p.}$ A	n	$q_{max}/q_{f.p.}$ A	n
Two-Dimensional Backward Facing Step	0.02	1.2	0.0465	1.3
Axially Symmetric Backward Facing Step	0.037	1.0	0.068	1.0
Two-Dimensional Blunt Base	0.018	0.77	0.034	0.7

TABLE 2.

AVERAGE AND MAXIMUM HEAT TRANSFER RATE PARAMETERS FOR CASES WITH ZERO BOUNDARY LAYER AT SEPARATION

$$q = B\,Re_h^m\,q_{f.p.}$$

	$q_{ave}/q_{f.p.}$		$q_{max}/q_{f.p.}$	
	B	m	B	m
Sharp Protruding Leading Edge	0.04	0.27	0.057	0.34
Leading Edge Separation Bubble	0.0057	0.45	0.0076	0.45

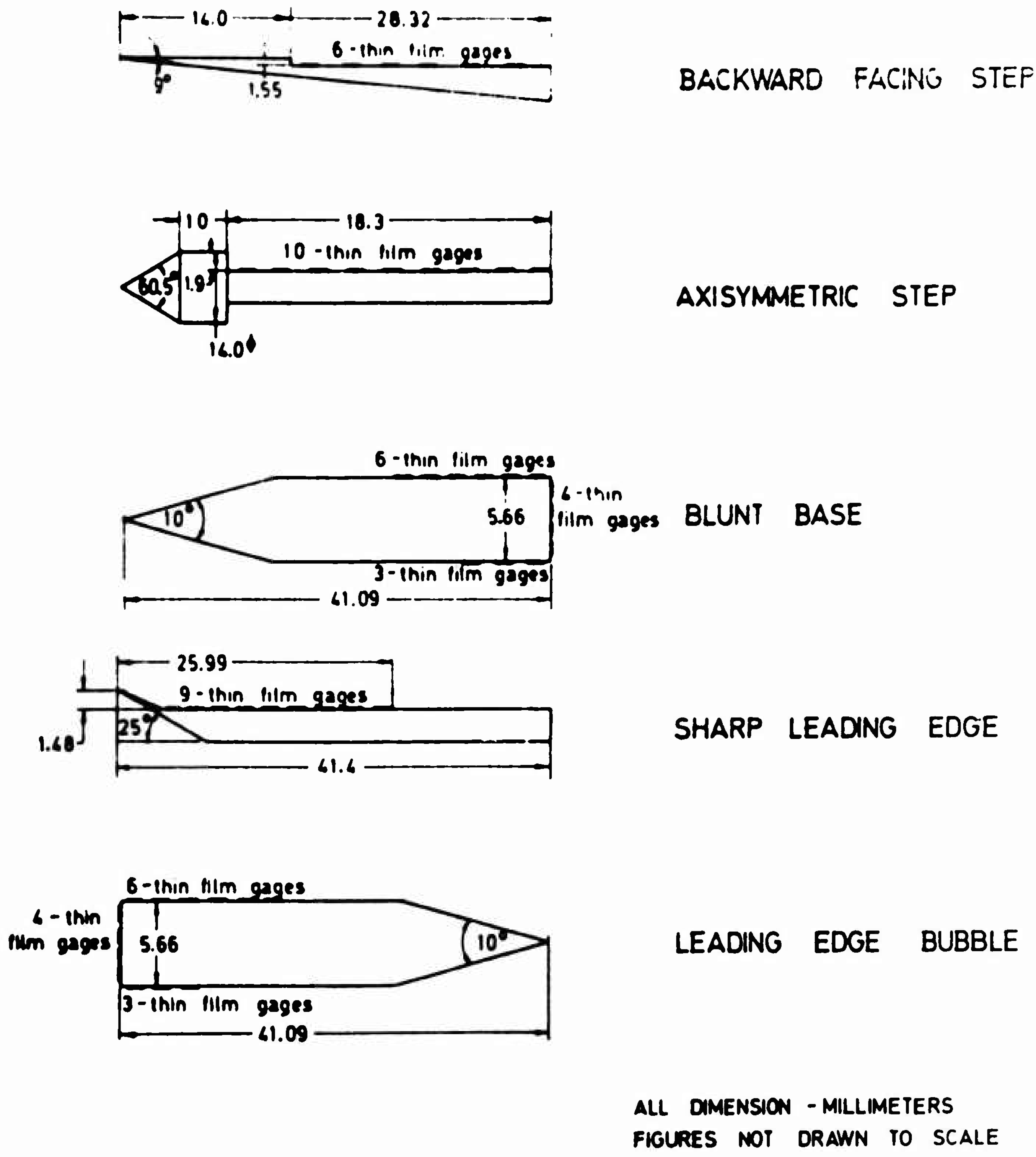

FIG. 1: Models for heat transfer measurements

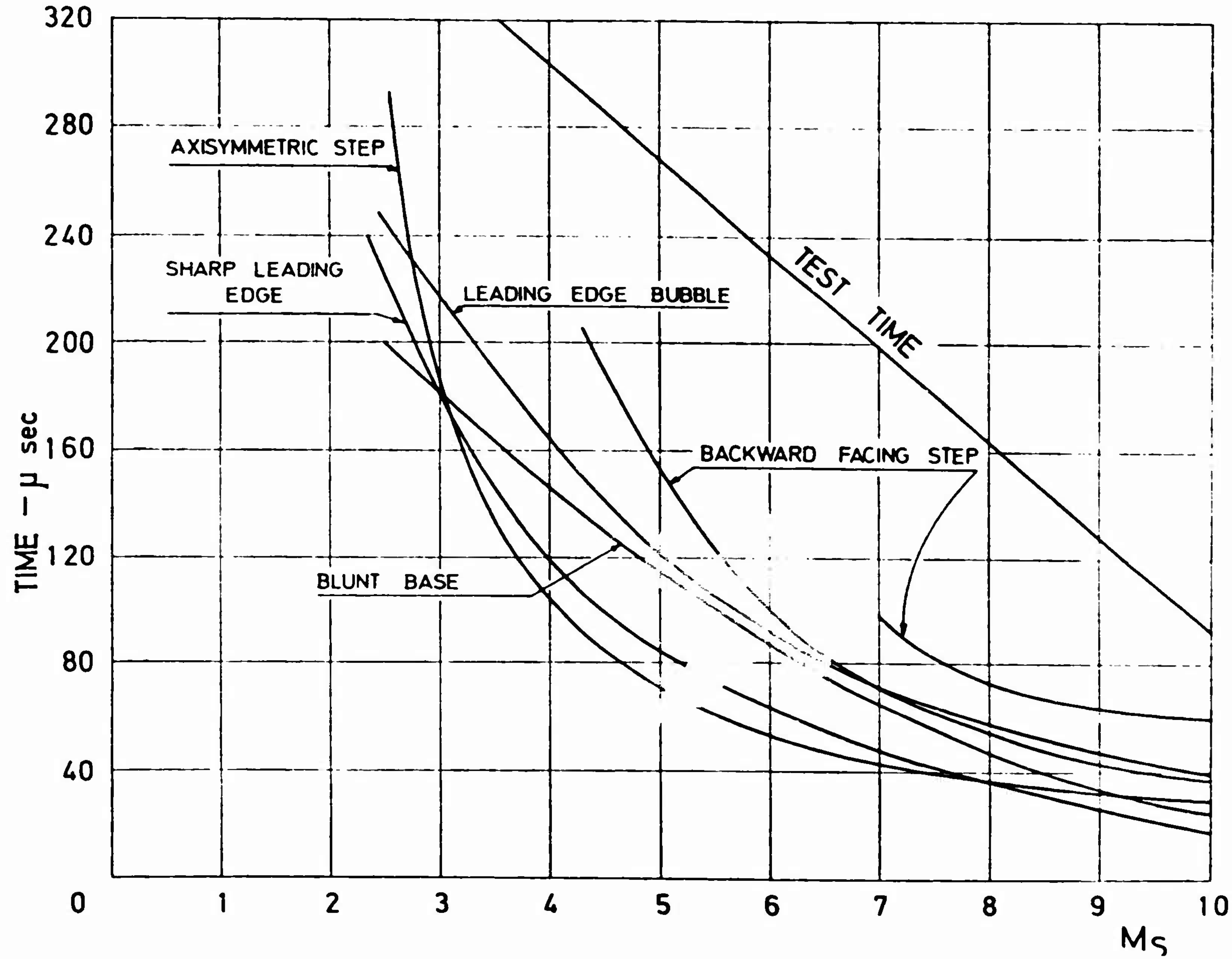

FIG. 2: Time for establishment of steady conditions in the separated flows

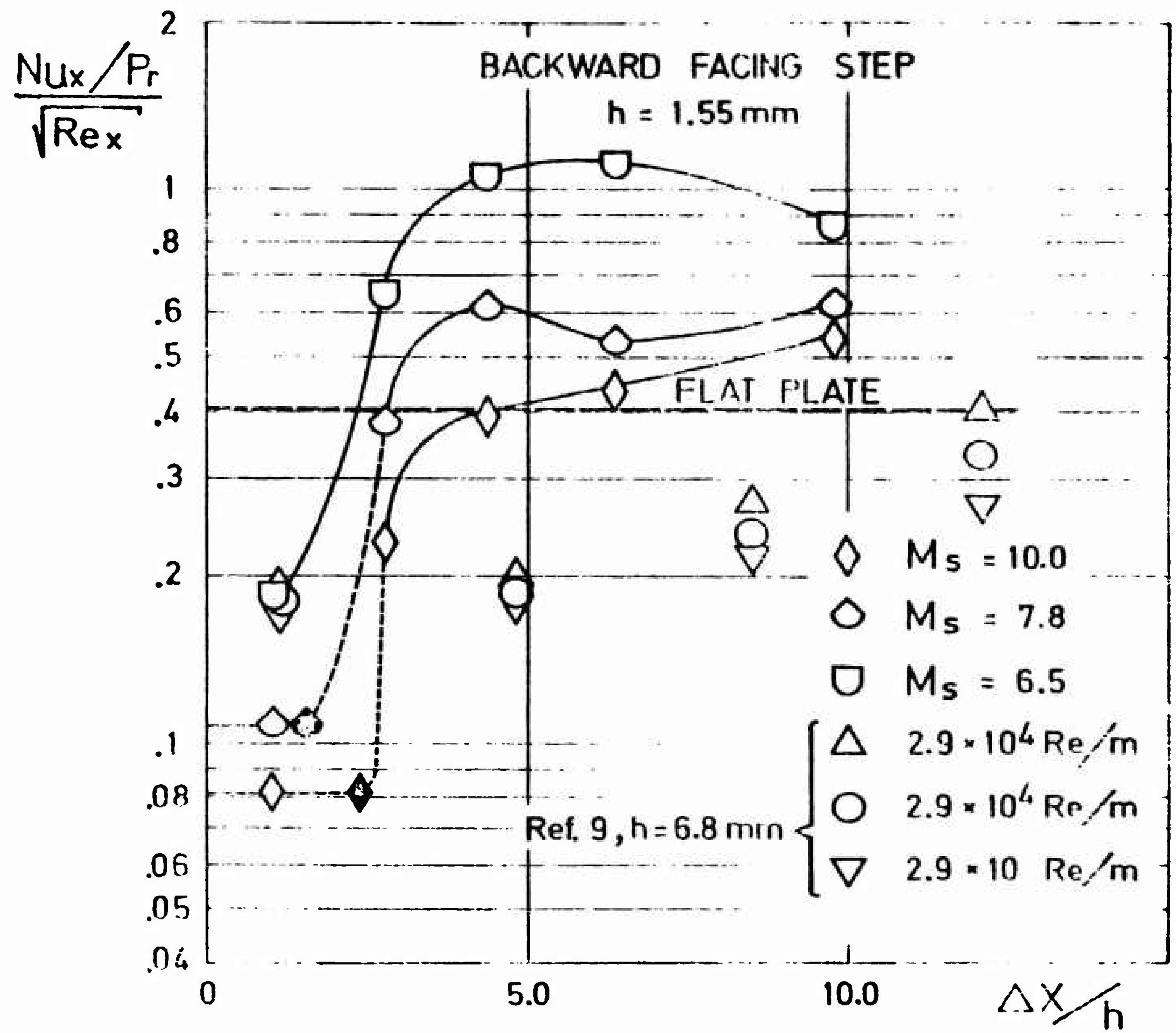

FIG. 9: $Nu_x/Pr\ Re_x^{1/2}$ as a function of $\Delta x/h$ for the two-dimensional step model

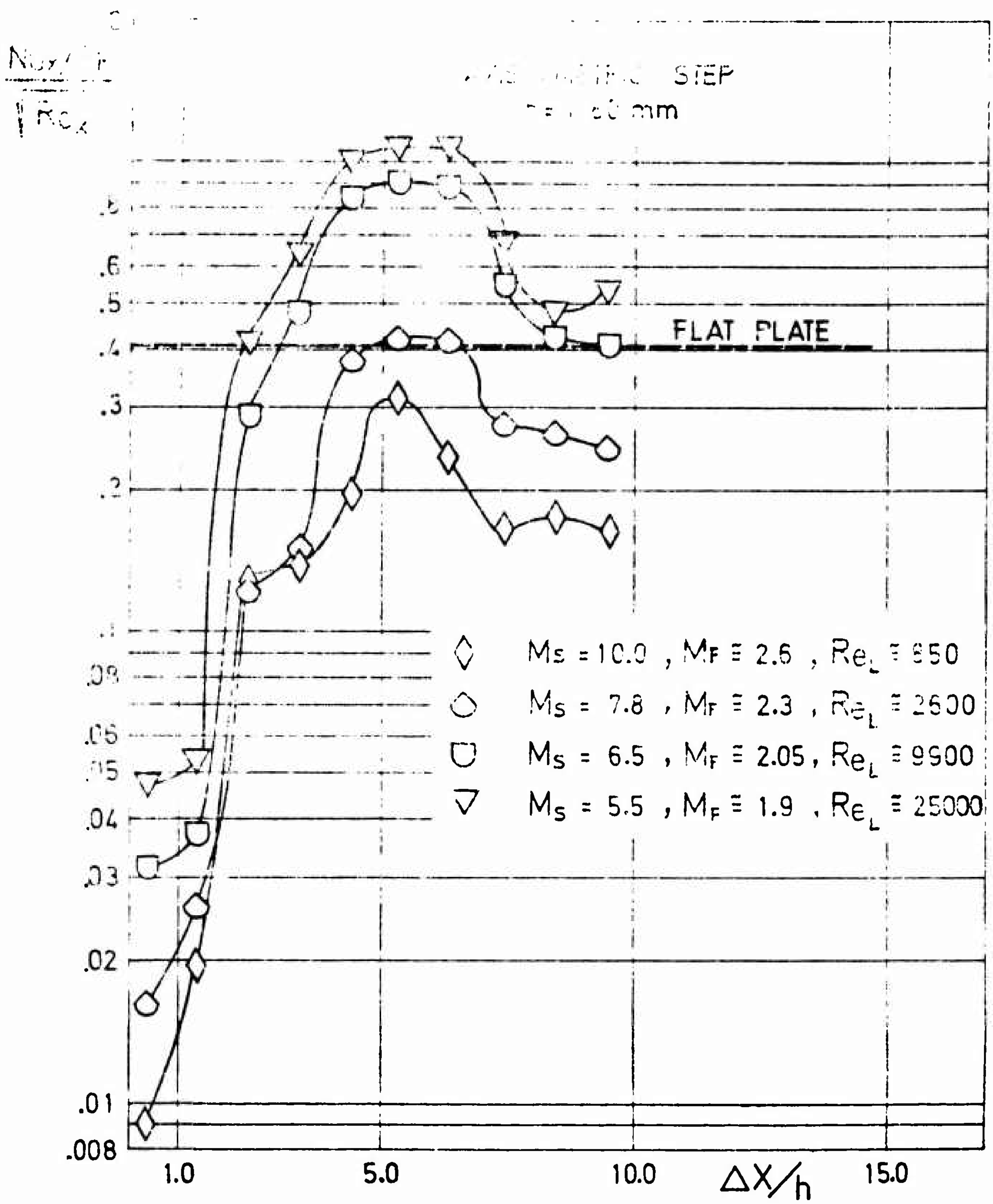

FIG. 4: $Nu_x/Pr\, Re_x^{1/2}$ as a function of $\Delta x/h$ for the axisymmetric step model

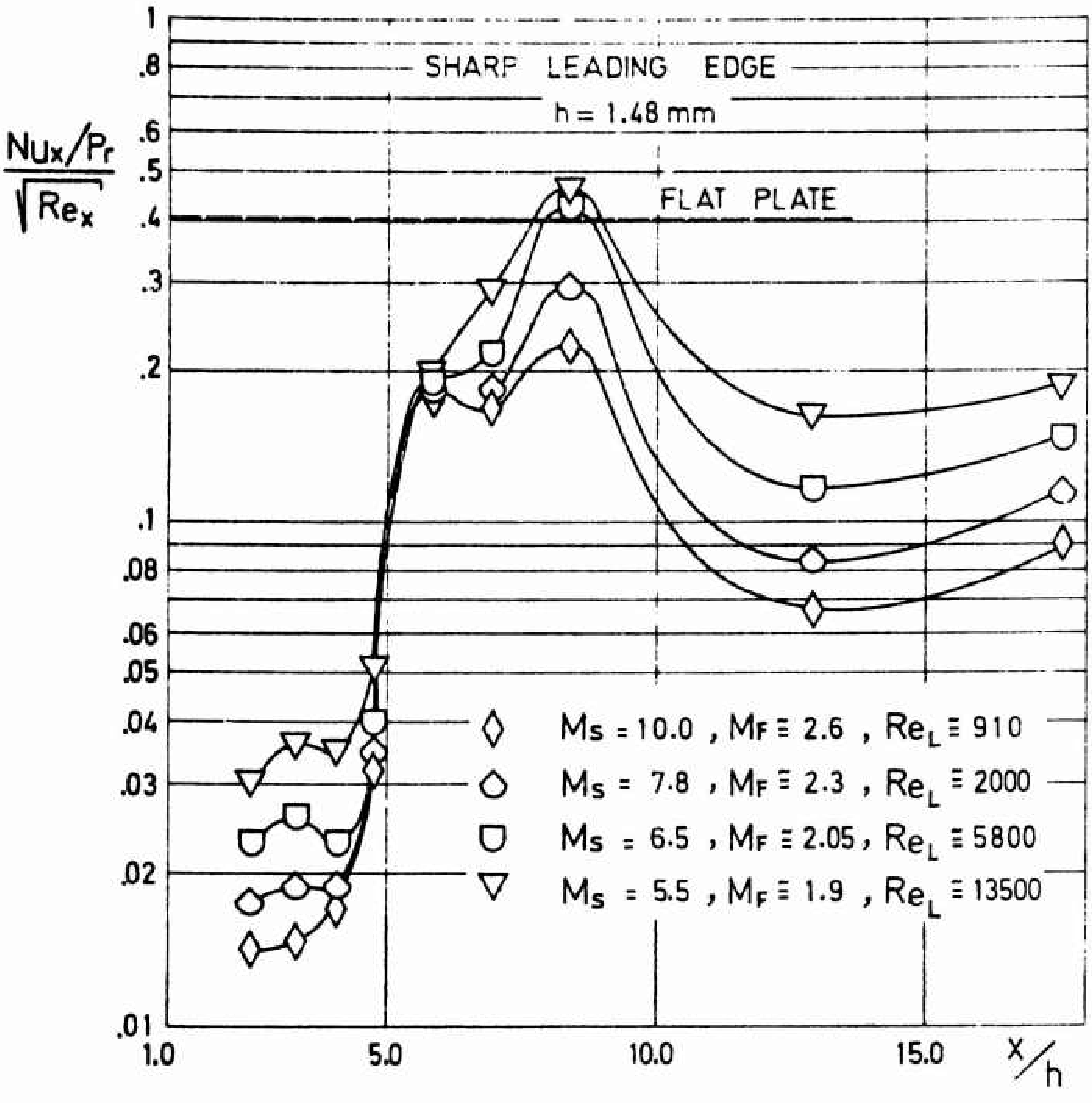

FIG. 5: $Nu_x/Pr\,Re_x^{1/2}$ as a function of $\Delta x/h$ for the sharp leading edge model

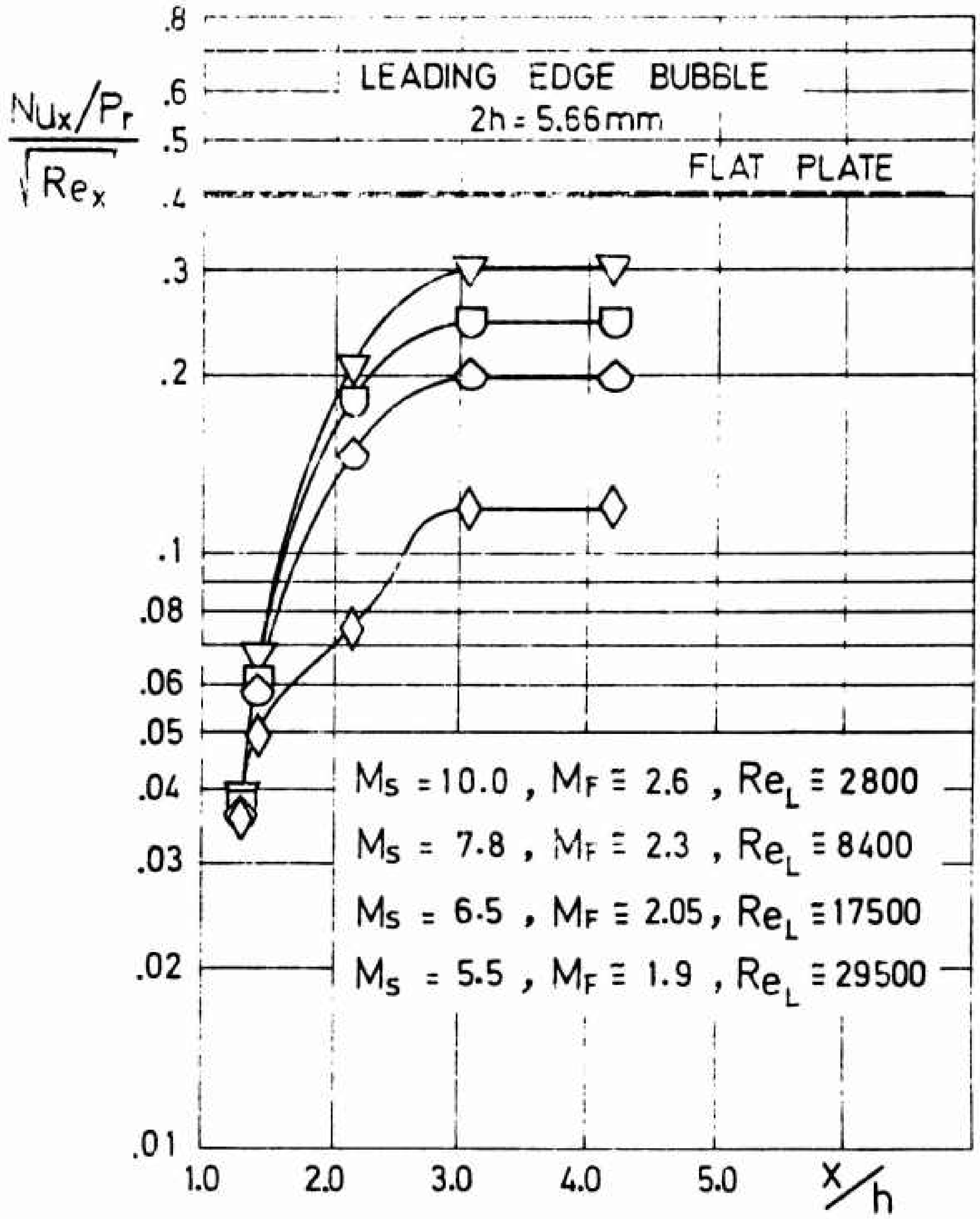

FIG. 6: $Nu_x/Pr\ Re_x^{1/2}$ as a function of $\Delta x/h$ for the leading edge bubble model

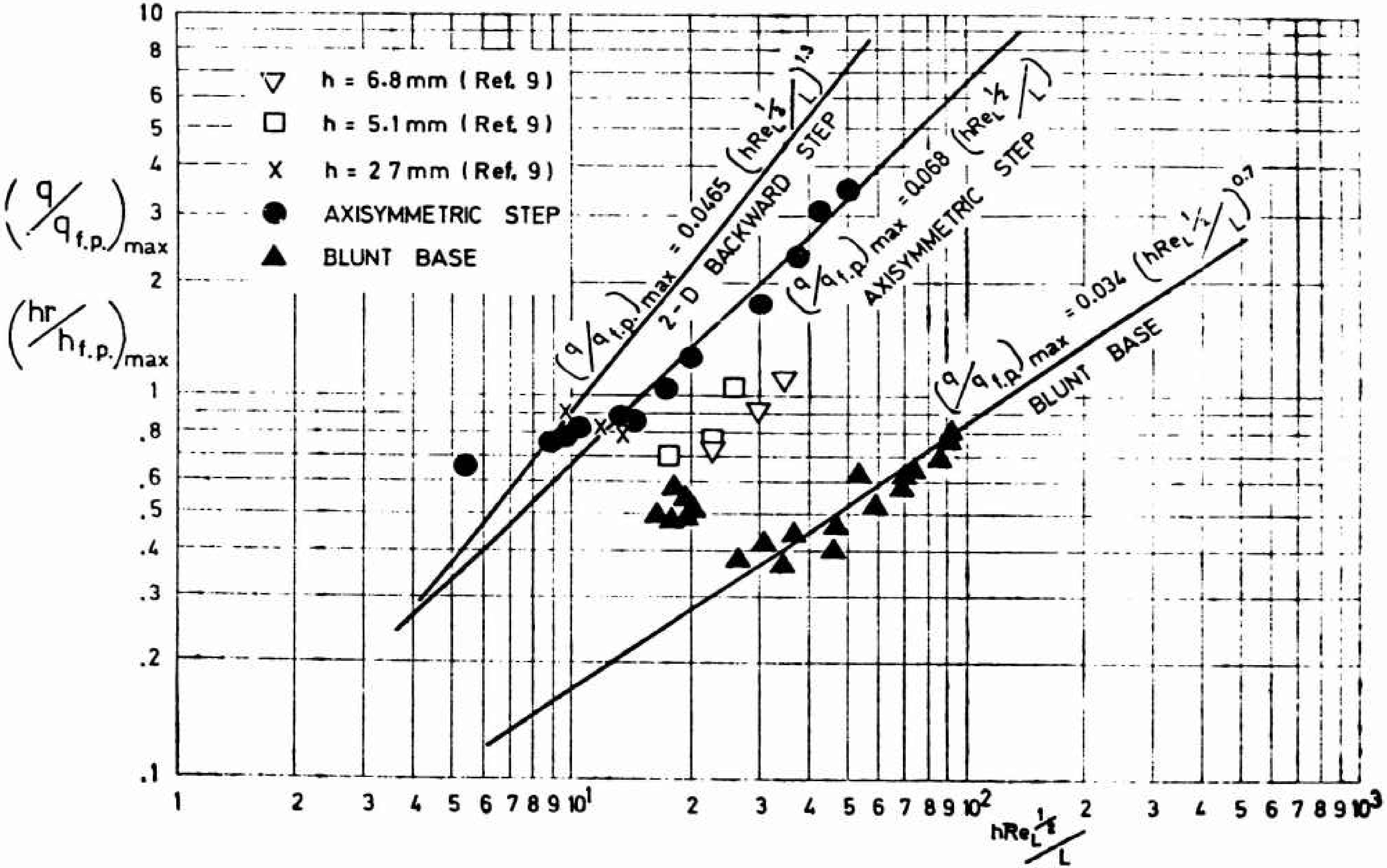

FIG. 7 : $q/q_{f.p.}$ as a function of $hRe_L^{1/2}/L$

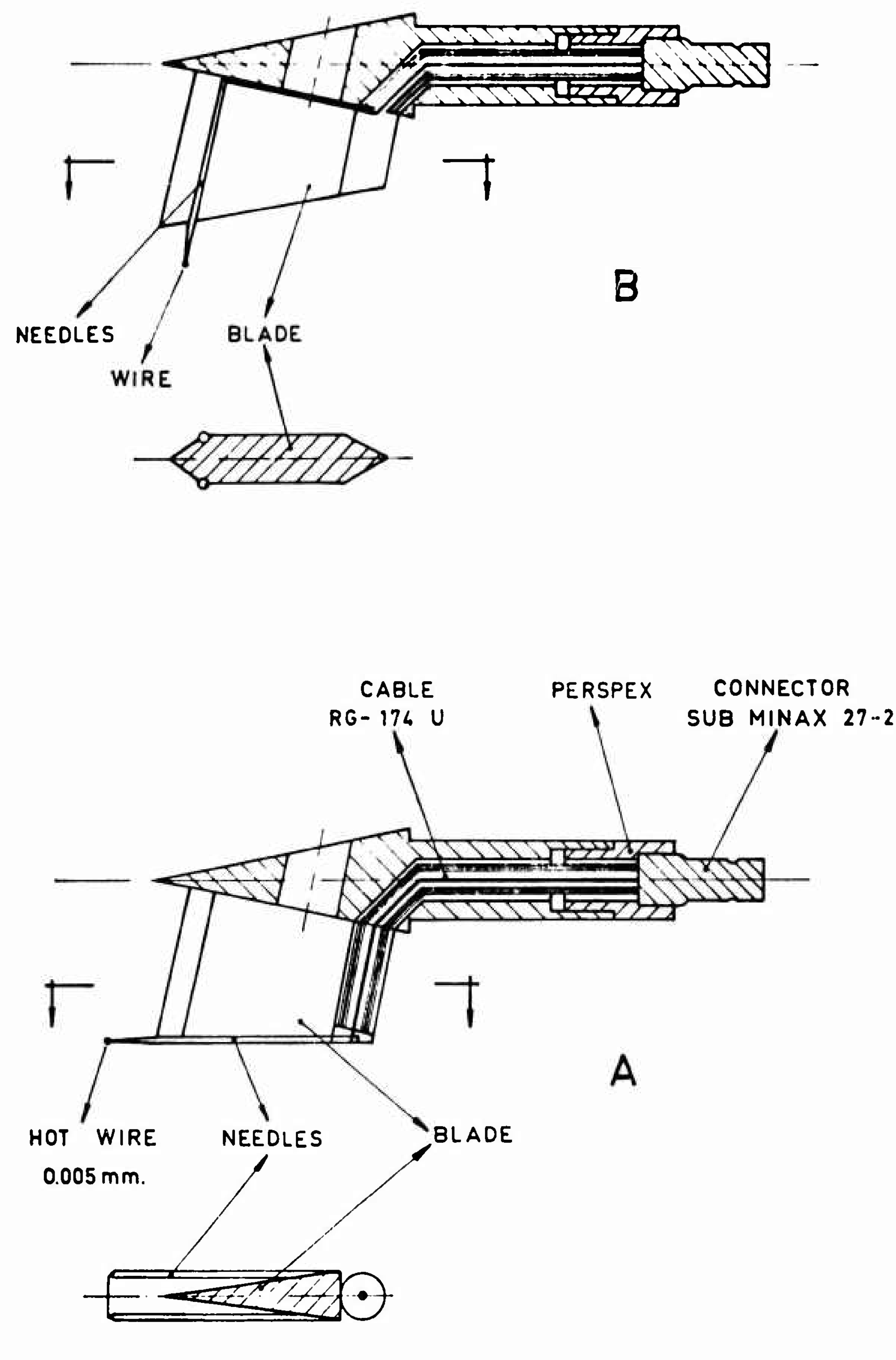

FIG. 8 HOT WIRE PROBES

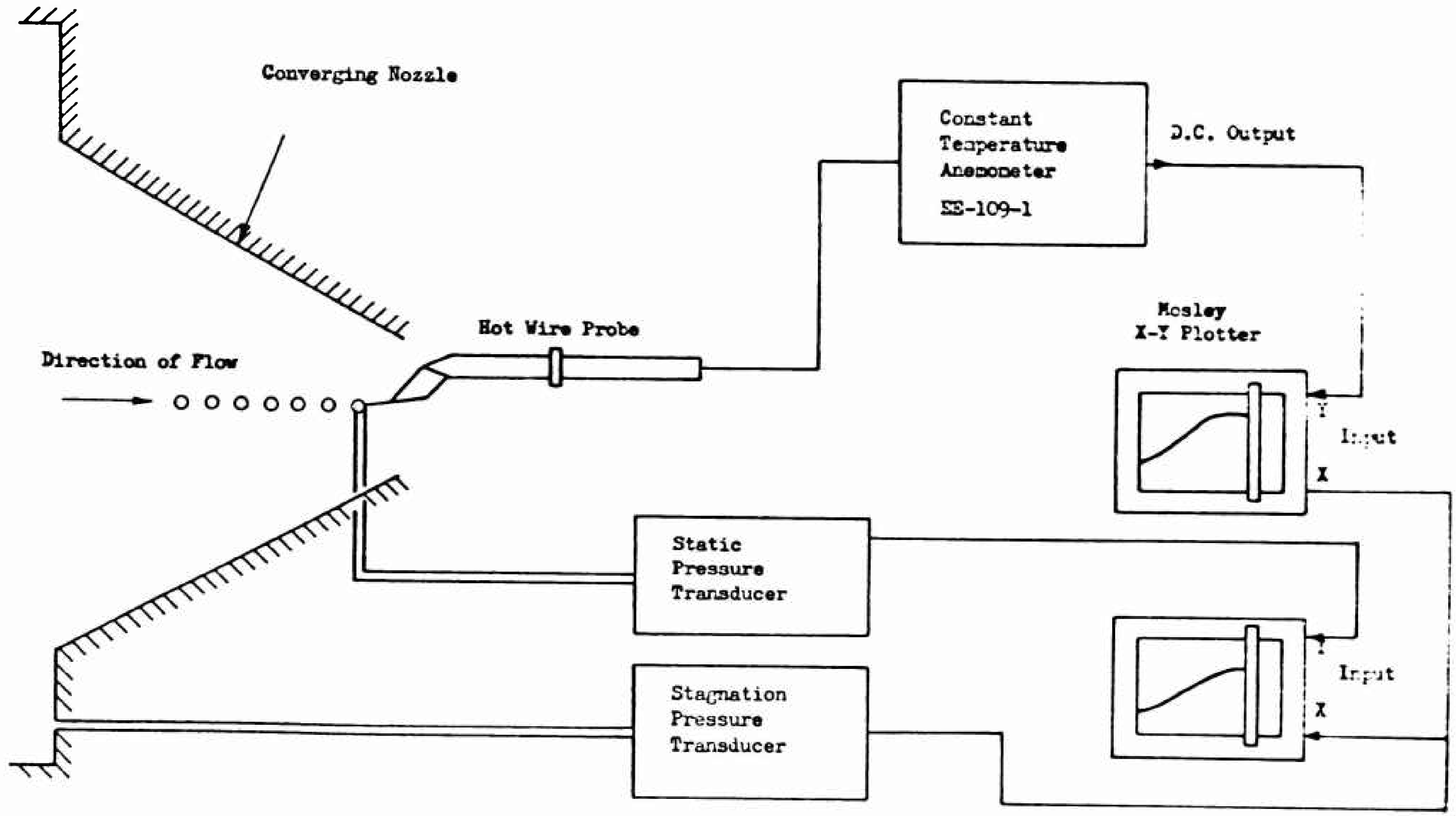

FIG. 9 A diagram of the calibration system in sub-sonic flow

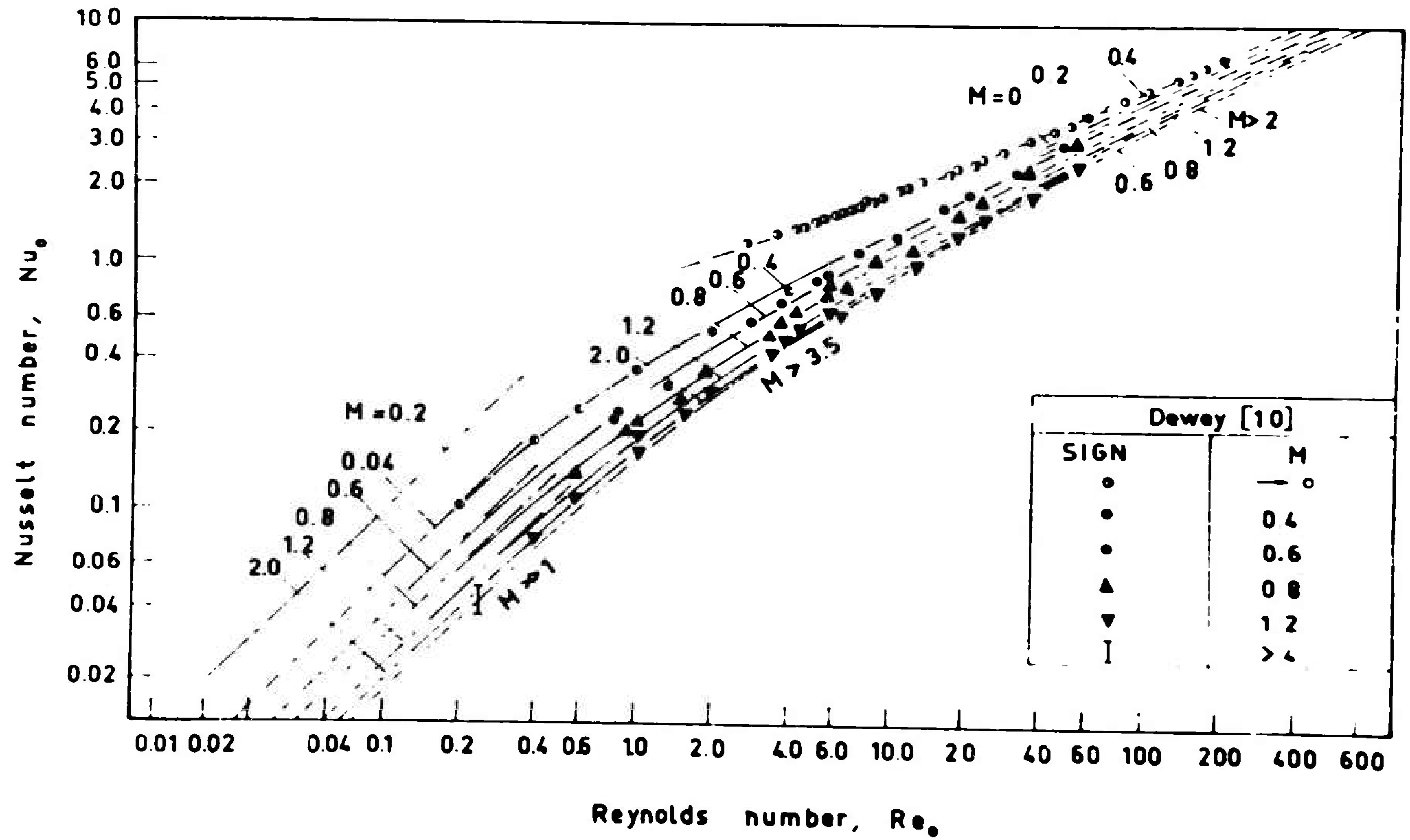

FIG. 10 Empirical correlation of cylinder heat-transfer at low Reynolds numbers

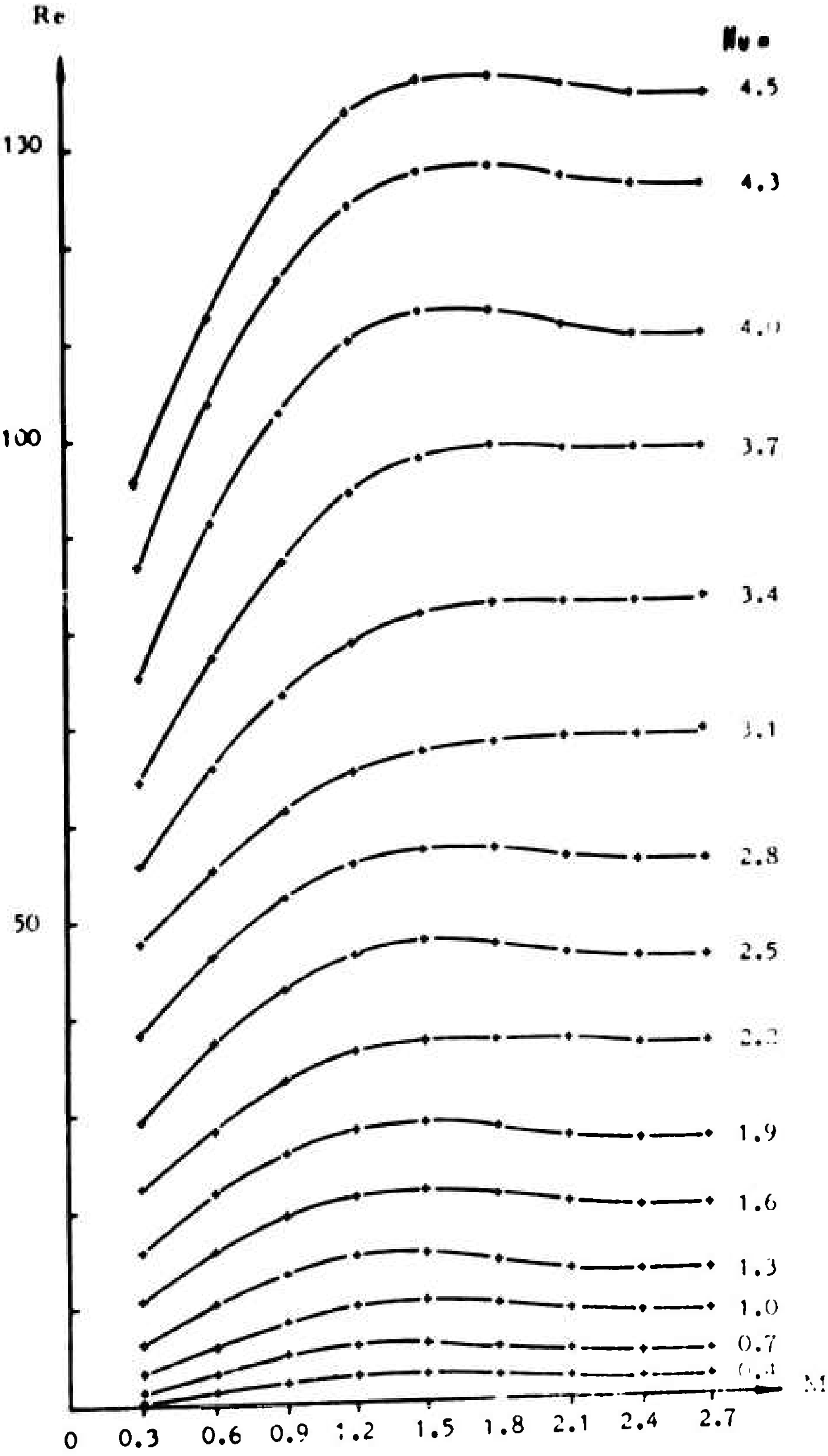

FIG. 11 Reynolds number dependance on Mach number with Nusselt Number as a parameter

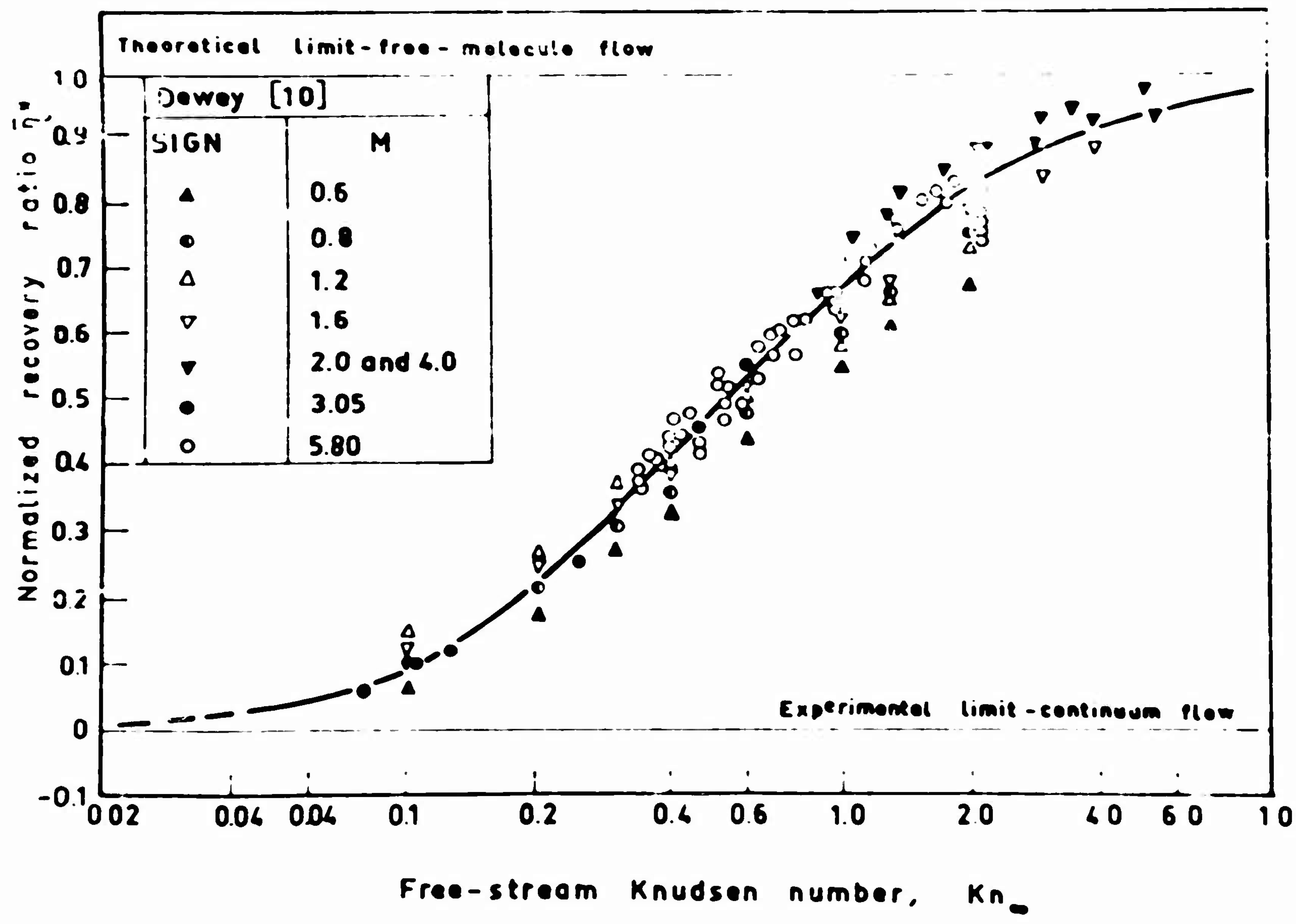

FIG. 12 Recovery factor variation with Knudsen number

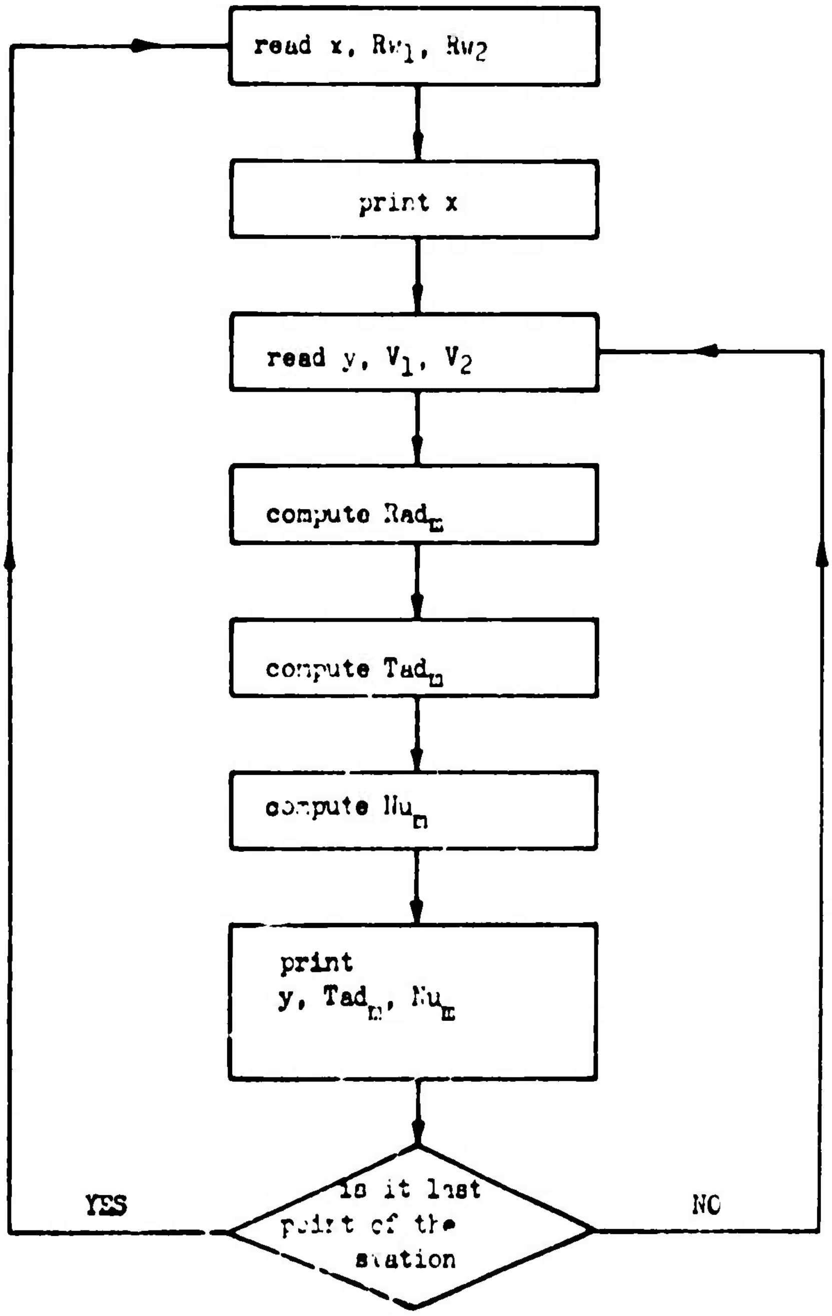

FIG. 13 Flow chart of the Data Reduction Stage 1.

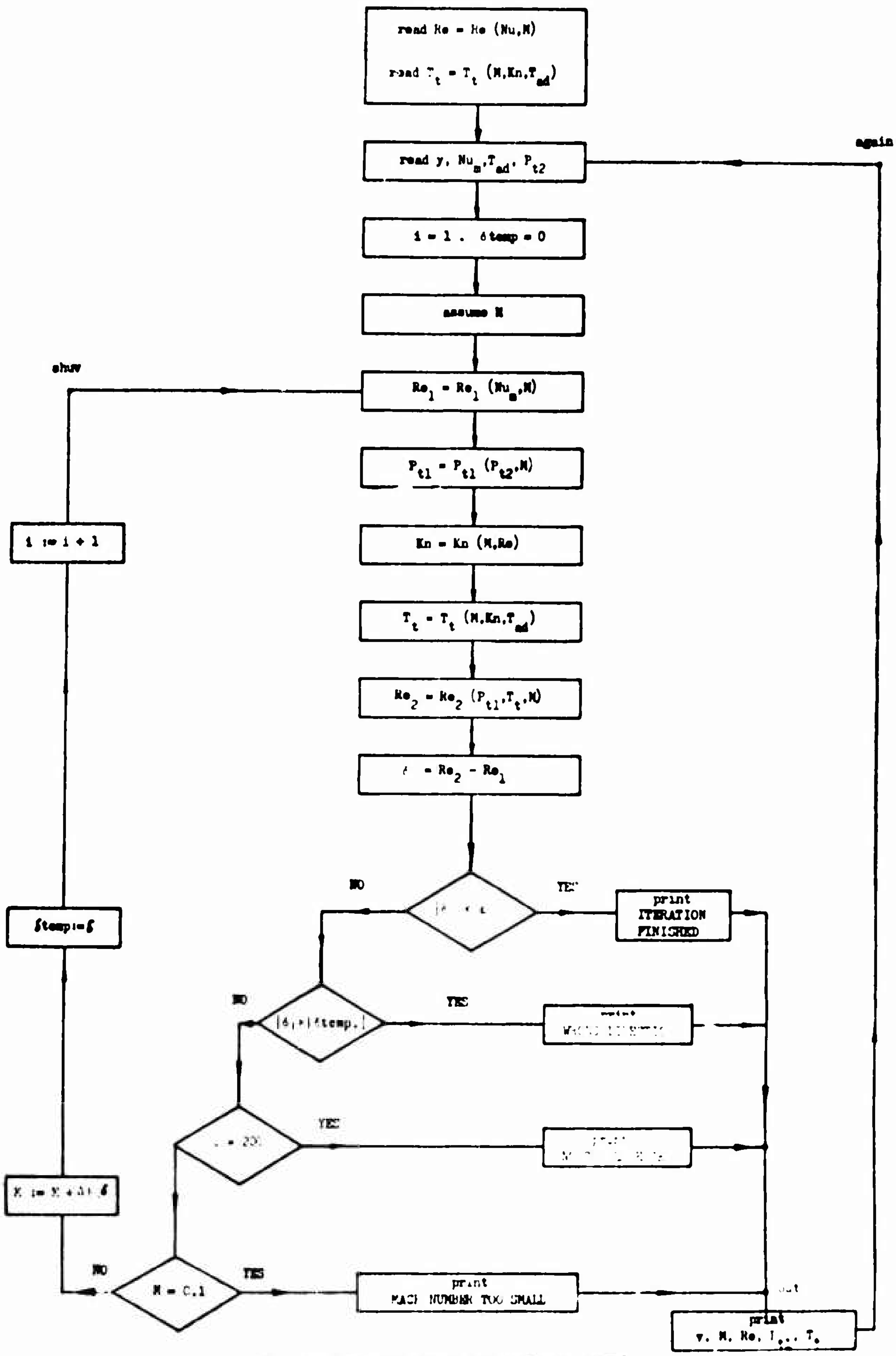

FIG. 14 Flow Chart of the Data Reduction Stage 2

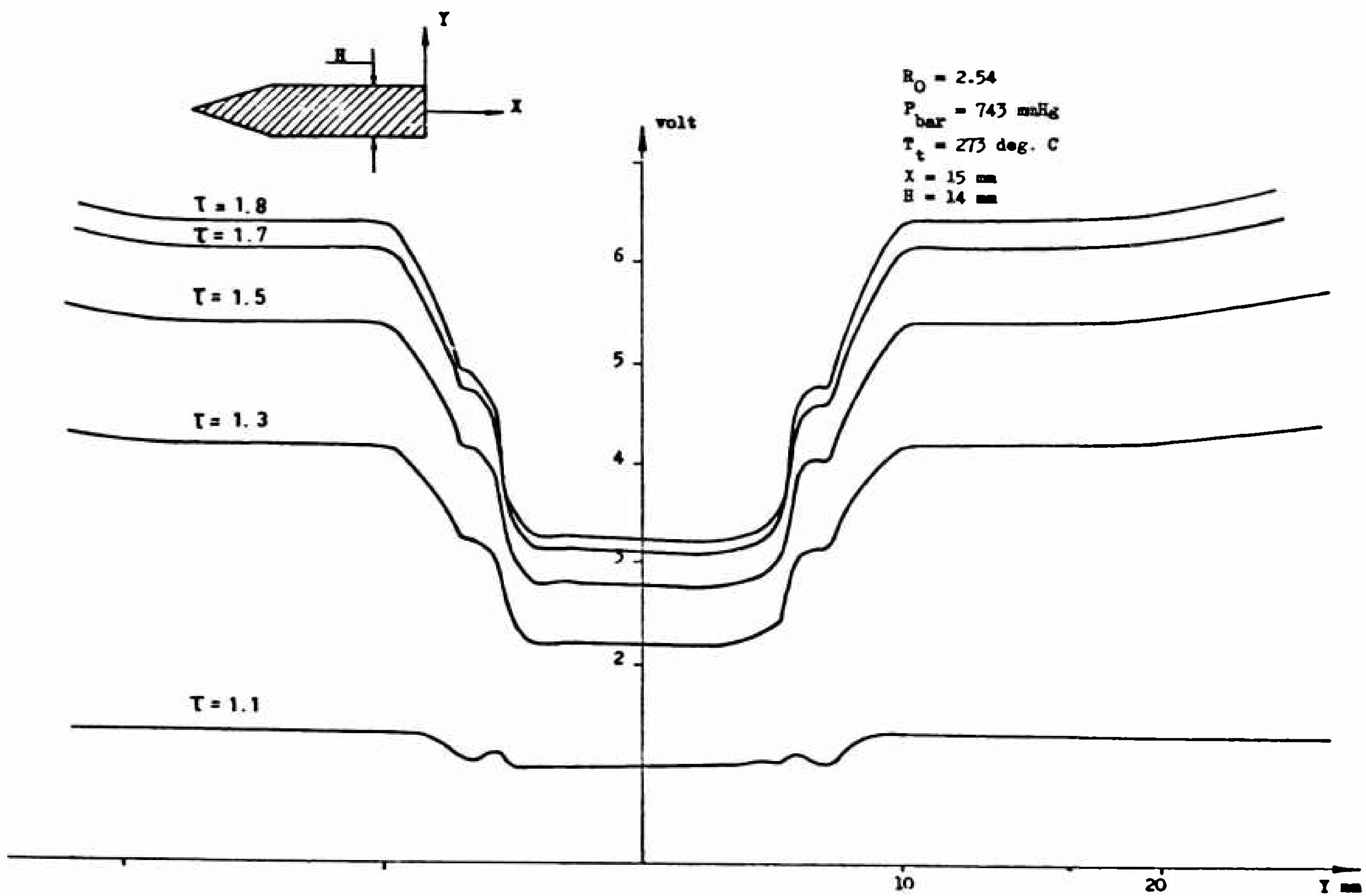

FIG. 15 Typical results of a measurement with a Hot-Wire

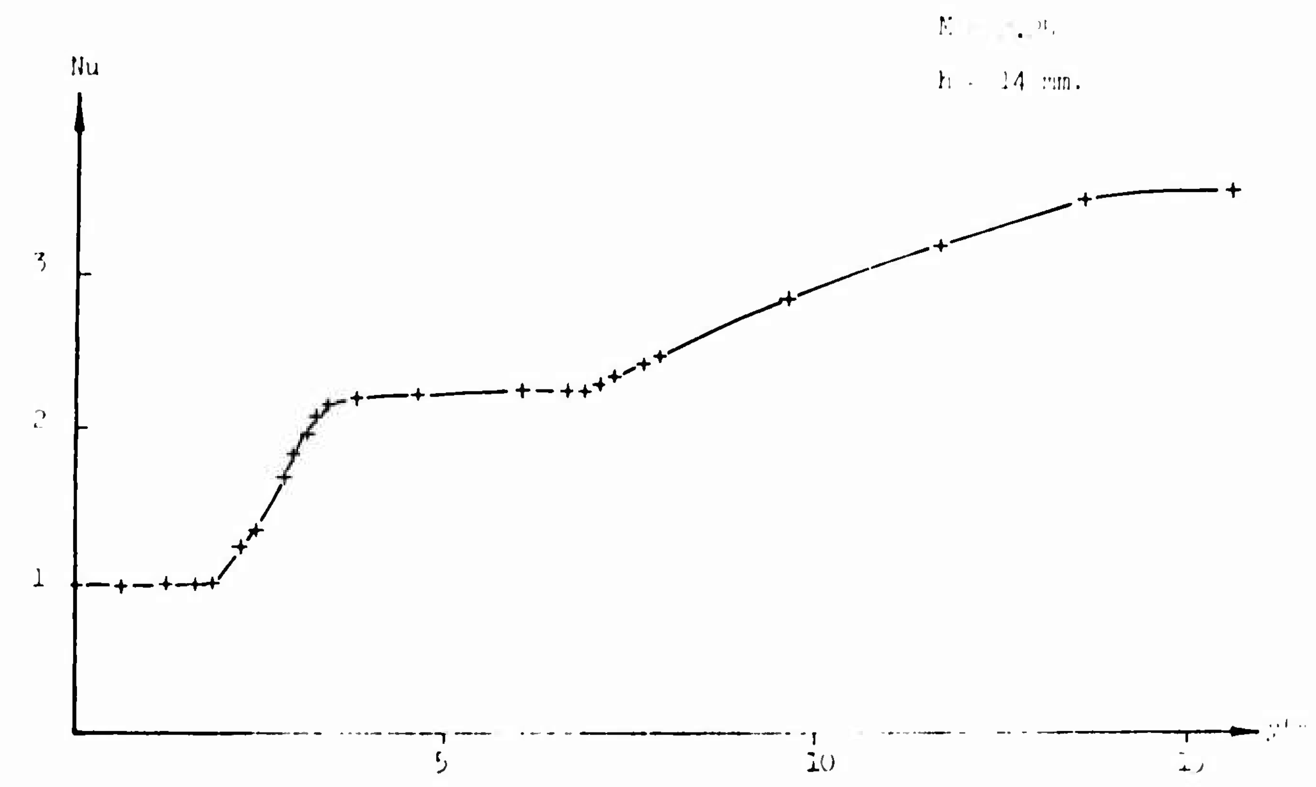

FIG. 16 Nusselt number distribution at x = 13 mm

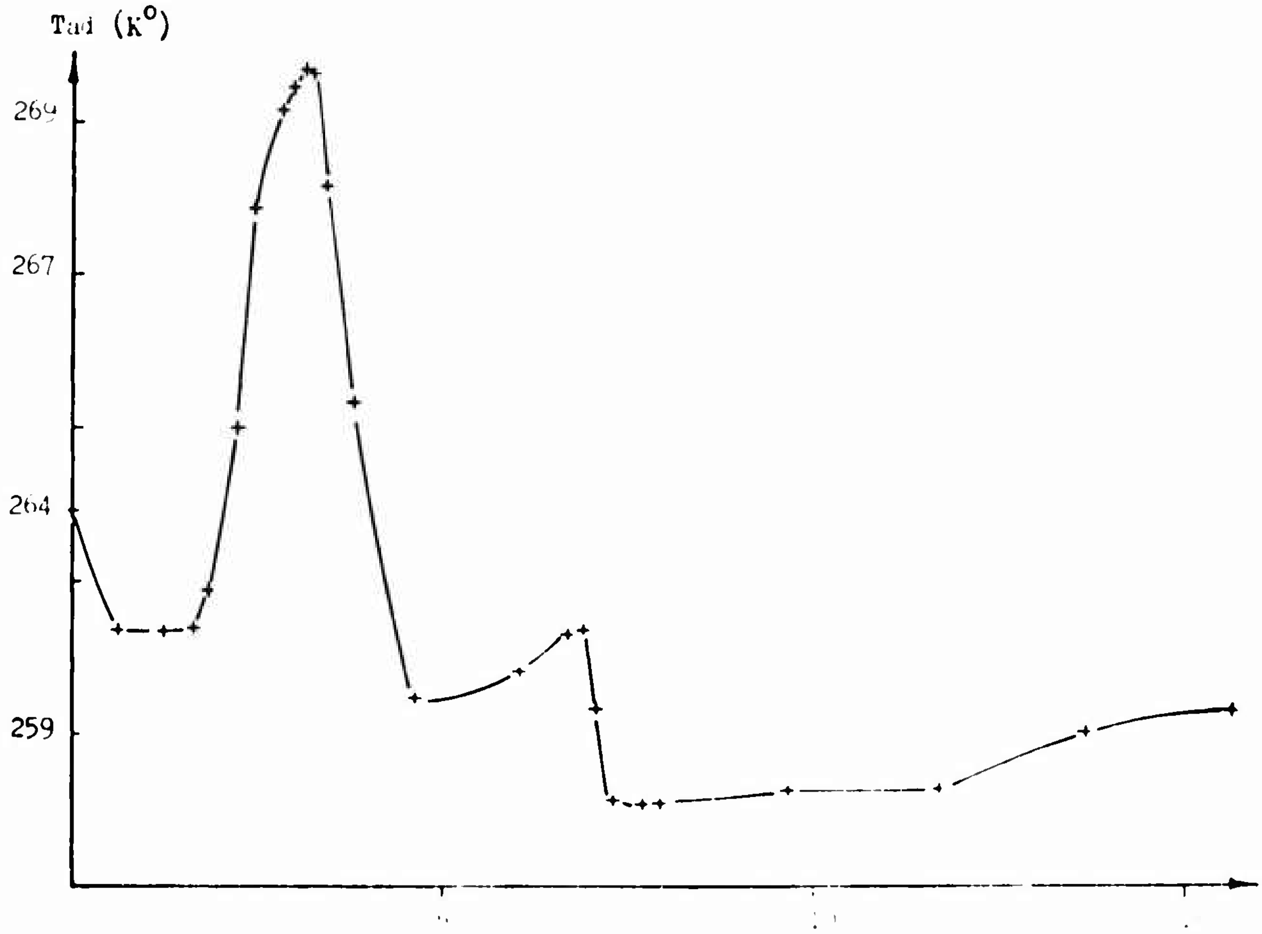

FIG. 17 Recovery Temperature distribution at x = 13 mm

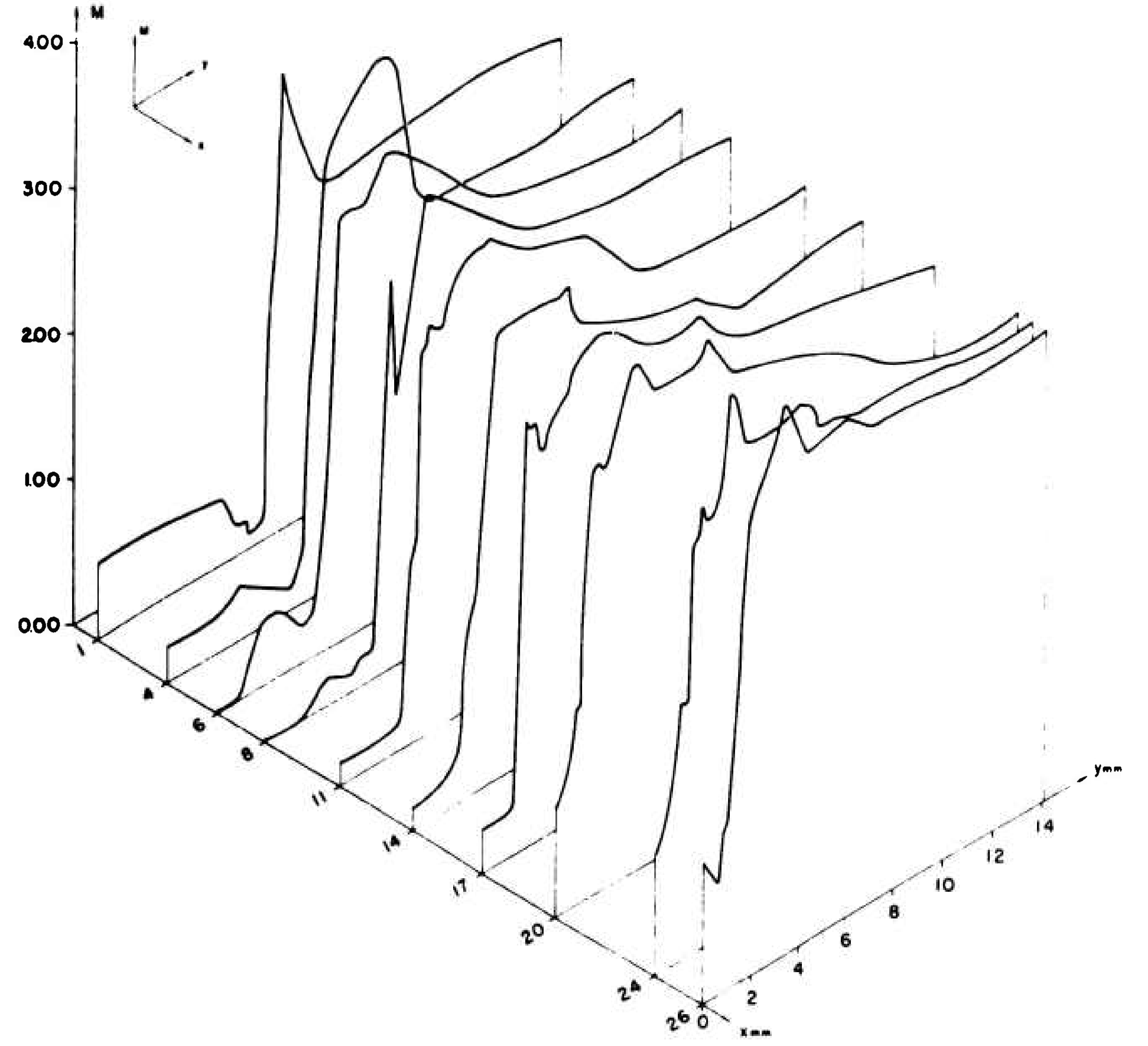

fig. 1S Mach number distribution in the flow field

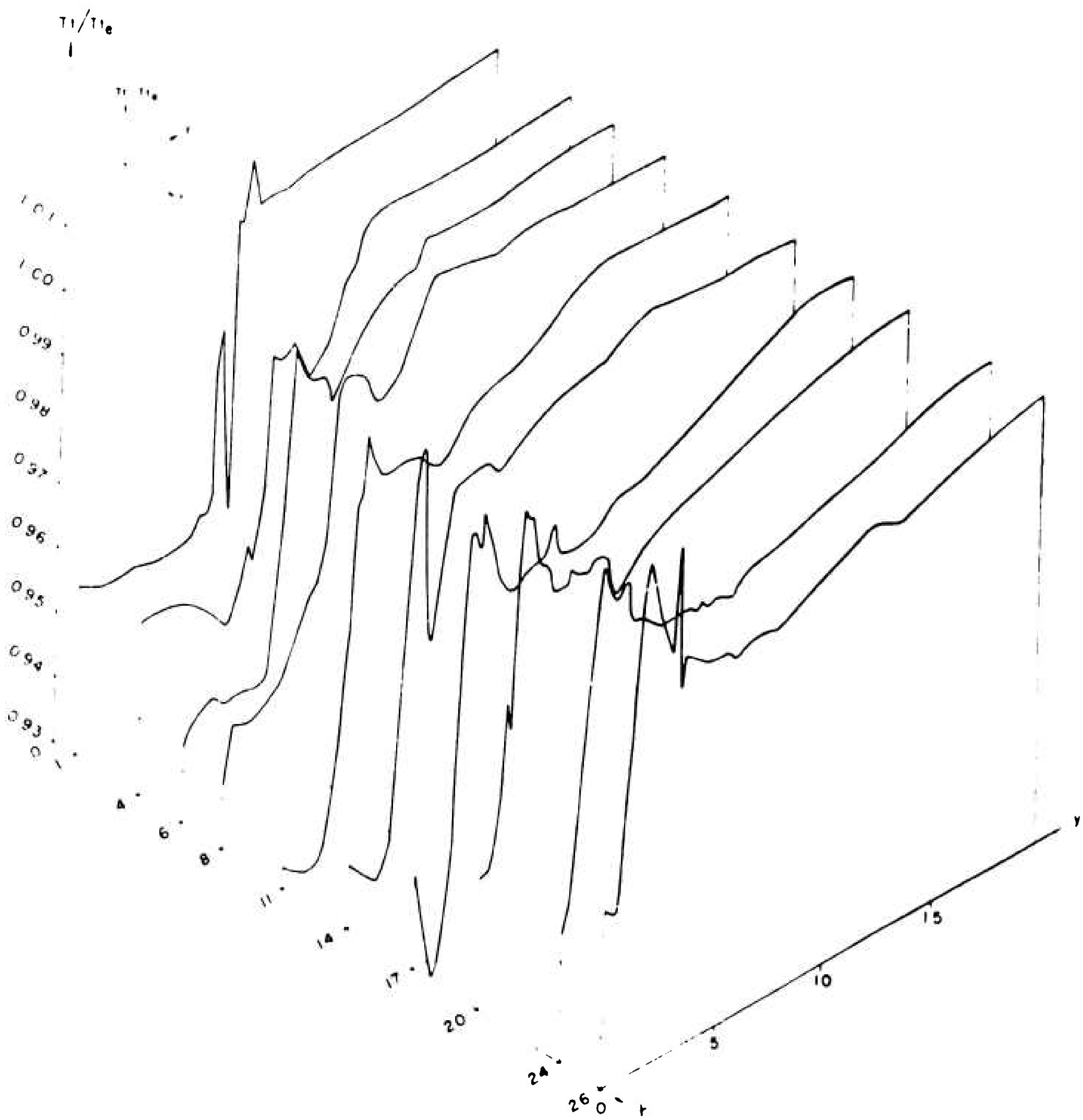

fig 10 Total temperature distribution in the flow field

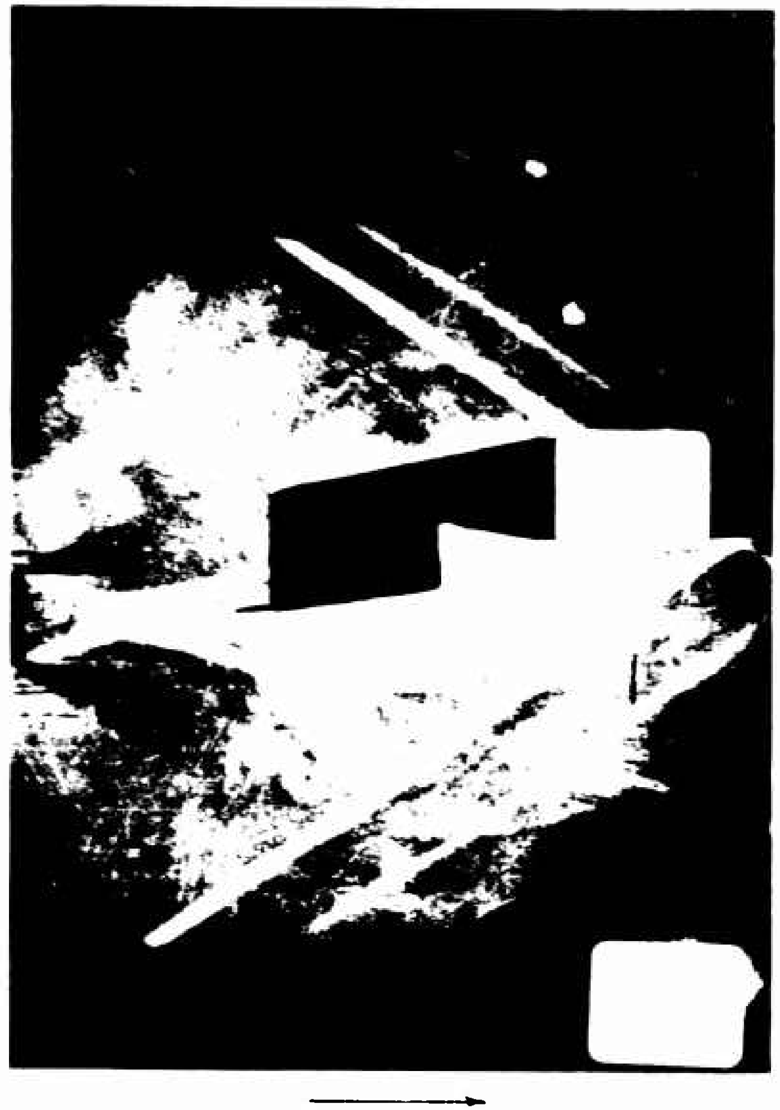

FIG. 20 Shadow picture of the flow with Hot-Wire probe

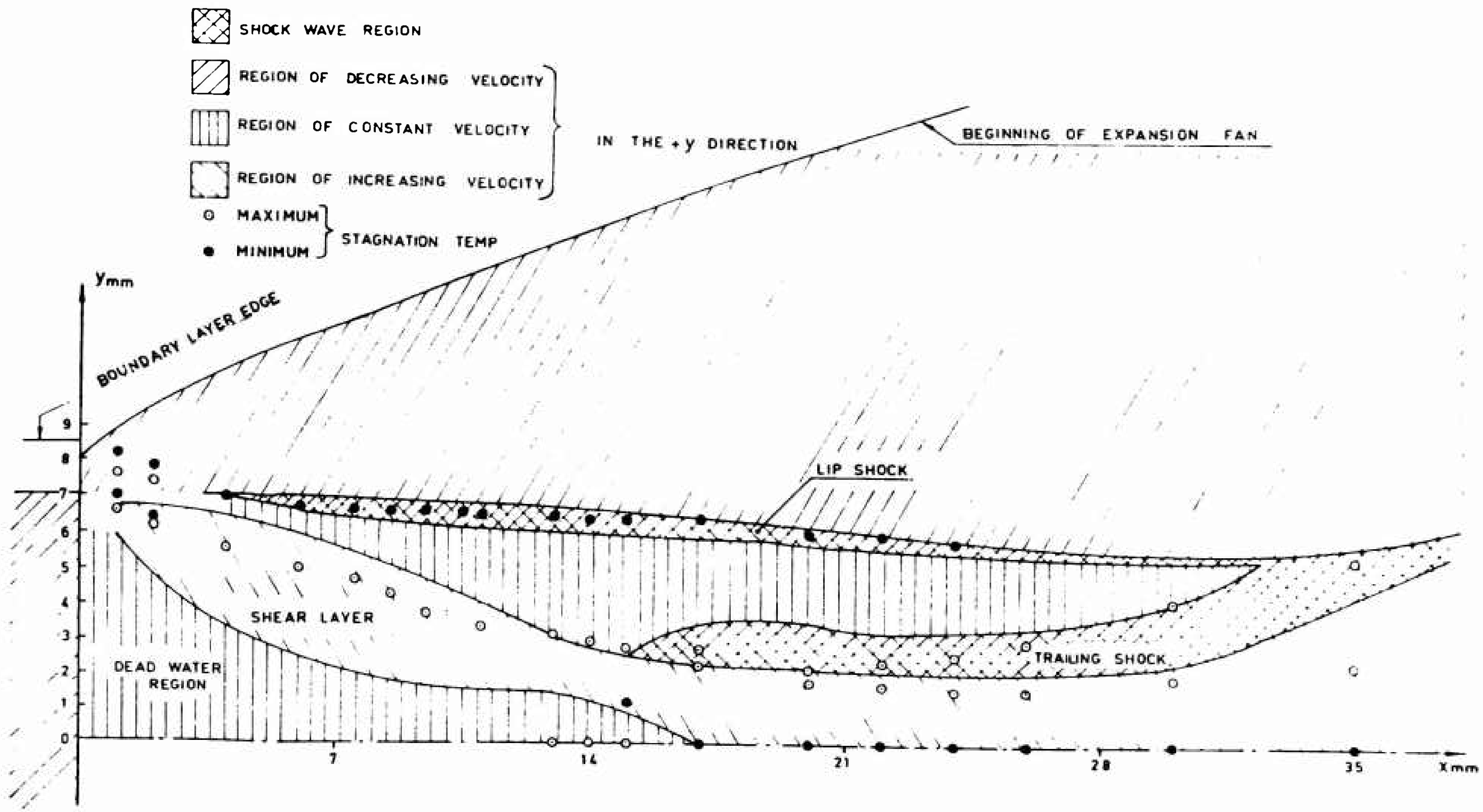

FIG 21 FLOW FIELD M= 2.25 ACCORDING TO THE PRESENT WORK

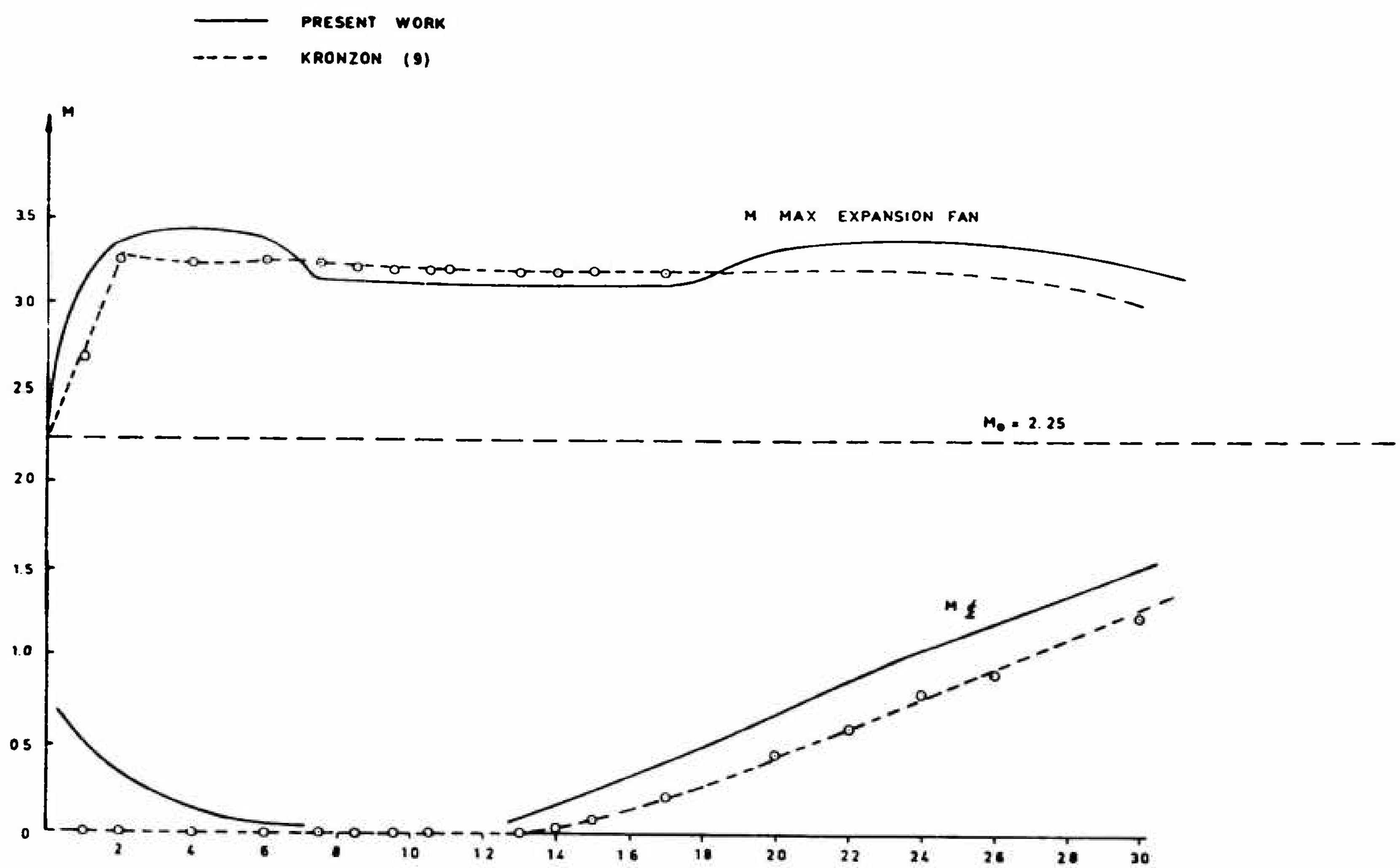

FIG 22. MACH NUMBER DISTRIBUTION ALONG THE CENTERLINE AND AT THE END OF THE EXPANSION FAN

Unclassified
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13 ABSTRACT

This report summarizes some of the research carried out under contract F 61052-69-C-0020 during the year 1st September 1968 to 31st August 1969.

Laminar and transitional heat transfer rates were measured in various base type separated flows in the shock tube. It was found that maximum and average heat transfer rates are correlated by the parameter $(hRe_L^{1/2}/L)$ for models with an initial boundary layer and by Re_h for models with leading edge separation.

The application of the hot wire technique for measurements of the flow field in the supersonic near wake is studied. It is shown that using the measurements of a hot wire probe and a total pressure probe enable the determination of all the required physical parameters of the dissipative flow field in the near wake. The flow field behind a blunt two dimensional base model is measured at Mach number of 2.25 and $Re_L = 1.5 \times 10^6$. Mach number and total temperature profiles are determined and the various zones in the flow field are identified.

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2. Transitional Heat Transfer Rates						
3. Base Type Separated Flow						

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